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ABSTRACT

A simulated dryer was used to examine heat flux and drying rates possible with a high-intensity gas-heated paper dryer. We examined the effects of surface temperature, felt tension (mechanical pressure), and other factors on drying rates in preheated and room-temperature sheets at 60% solids. The results of this study show that significant gains in drying rates may be achieved by increasing the applied pressure when the surface temperature exceeds 200°C.

While the absolute values of heat flux observed in this study are larger than those seen in a mill, the data are still useful in determining key trends such as the increase in heat transfer that may occur with increased pressure and temperature. Future work is underway to better simulate industrial drying. However, the data raise the possibility that industrial cylinder drying may be operating well below its potential.

BACKGROUND

To overcome the practical limitations of steam as the heat source in drum driers, ABB Flakt Ross has developed the Gas Heated Paper Dryer™ that can be installed as a retrofit in a conventional drum dryer section (1). This dryer uses high-velocity impingement of combustion gases inside a dryer drum to heat the shell to temperatures above those possible with conventional steam systems. For example, surface temperatures in the range of 200-300°C are easily achieved, compared to a typical range of 110-170°C for steam-heated dryers. To better understand the capabilities and limitations of high-intensity drying, we desired information on the effect of mechanical pressure on heat transfer rates for several paper types. We were particularly concerned about the possibility of high steam pressure at the paper-drum interface causing "lift off," resulting in poor thermal contact between the surfaces.

Lift off is not commonly observed in drum drying. Typical levels of fabric tension are believed to provide enough mechanical pressure (typically 1-5 kPa) to overcome the lifting effect of internal vapor pressure in the sheet generated by conventional drying. However, as drying rates increase, increased vaporization in the sheet may lead to steam pressures that could cause separation of the sheet from the drum. In this case, increased fabric tensions will be needed.

Some mill personnel have reported that drying can decrease when steam-filled drums are too hot. A common explanation has been that the high temperatures can "seal" the surface of the sheet, making subsequent vapor transport through that surface more difficult. In some cases, lift off may have played a role as well.

Many efforts have been made to increase paper drying rates by increasing temperatures of contacting surfaces. Impulse drying is one of the most dramatic examples (2,3,4). Impulse drying is a variation of wet pressing with the pressing surface heated to 250-400°C. Internal vapor formation in the nip may assist liquid water removal through displacement and rewet resistance. Press drying research has also shown that significantly higher drying rates are possible when a sheet is properly restrained against a hot surface (5).

Ahrens et al. (6) investigated the potential of increased drum temperature and fabric tension to improve drying. Using a drying simulator, they examined moisture loss in handsheets for contact times between 5 and 35 seconds with surface temperatures between 128 and 241°C. Mechanical pressure ranged from 1.7 to 23 kPa. They noted that increased mechanical pressure offered little benefit at low temperatures, but contributed significantly to increased drying at higher temperatures. This was explained in terms of lift off. In a related study, Ahrens (7) reported heat fluxes in 205-gsm unbleached kraft sheets under high intensity drying conditions. Heat fluxes several times higher than those in conventional dryers were reported.

EXPERIMENTAL APPROACH

As in the studies of Ahrens and others, we desired to simulate high intensity drying in paper. Our approach differs from most previous lab-scale work in our efforts to simulate the contact time and the ingoing web temperatures and moisture levels that are used in commercial installations of the gas-heated dryer. Some measurements were also made in room-temperature sheets for simplicity.

Drying on a single high-intensity drum was simulated by bringing paper into contact with a heated platen for a controlled interval on the order of 0.5 seconds. The mechanical loading was adjustable to simulated practical contact pressures generated by a fabric under tension. Figure 1 shows a sketch of the drying simulator used in this study. A 12.7-cm (5-inch) paper disk is dried by placing it on a drying fabric resting on the surface of a mobile lower platen. The lower platen is raised pneumatically until it contacts and lifts a heated upper platen. The pressure applied by the upper platen is controlled by a low-friction counterweight system. The drying time is controlled by an electronic timer, which causes the lower platen to drop when the selected time has elapsed.

A load cell was mounted in the lower platen. An oscilloscope was used to permit observation of the transient mechanical pressure pulse during a drying event. Figure 2 shows a typical pressure pulse recorded from an oscilloscope screen. Several characteristics of virtually all pressure pulses in this study are evident in Figure 2. There is a pressure overshoot, followed by weak oscillations, with some noise or erratic vibrations as the load is released. The degree of these features varied from case to case. An extreme occurred in some runs at the lightest load (1.7 kPa pressure), where pressure overshoots up to 40% were seen.

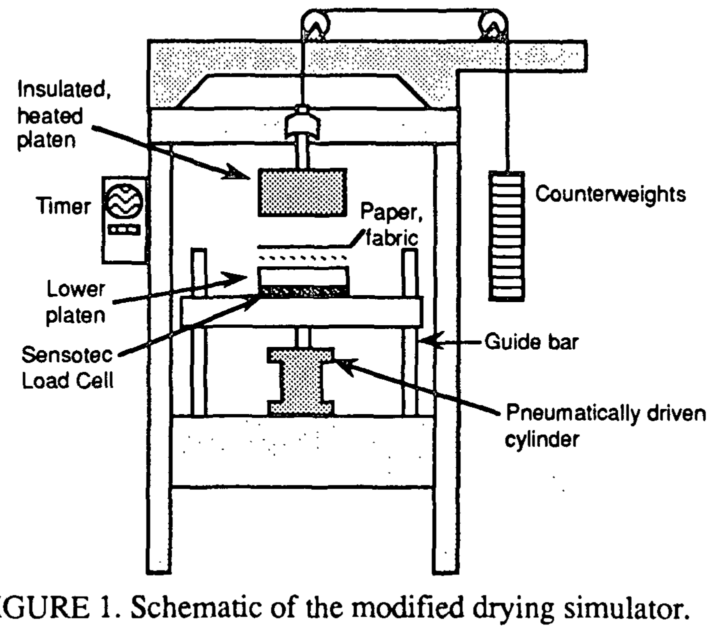

FIGURE 1. Schematic of the modified drying simulator.

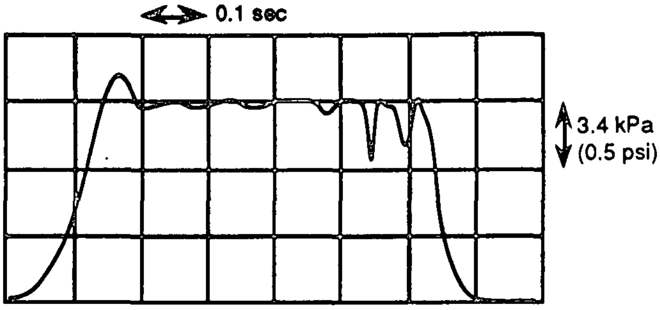

FIGURE 2. Trace of a pressure pulse for a run with a target pressure of 10.3 kPa.

Drying times were controllable in 0.1-second increments with an electronic timer that was triggered by the rising lower platen. Because some time is required to ramp up to full pressure, contact times of 0.55-0.7 seconds were required to achieve 0.5 seconds at full pressure, typical of the contact times on a single drum in a commercial machine.

Differing overshoot pressures and ramp rates could cause systematic error in comparing results at different pressures; in particular, the more rapid ramps at low pressures, coupled with the higher overshoot pressures sometimes seen in the 1.7 kPa runs, could tend to skew the low pressure data toward relatively higher peak heat fluxes and higher time-averaged heat fluxes and drying rates. If less time is spent in the inefficient ramp-up zone and more time is spent at full pressure (or an elevated overshoot pressure), heat transfer efficiency is increased.

The heated platen was cylindrical steel with a diameter of 15 cm. Three horizontal holes were drilled at nearly 7 cm above the drying surface to hold cartridge heaters that were controlled separately to maintain constant and uniform surface temperature. Temperatures across the surface typically fell within a 2°C range. The heated platen contained three vertical shafts for surface thermocouples (type-K eroding thermocouples, Nanmac Corp., Framingham, Mass.). They were made of steel to have the same thermal properties as the platen. Toward the end of the study, rare manufacturing defects were discovered in two of the the three thermocouples which had introduced errors in the temperature readings but did not appear to introduce detectable errors in the heat flux that was computed from the transient temperature change during drying. Later work with defect-free thermocouples has given heat flux results entirely consistent with the data presented here.

A single drying fabric sample was used in all tests of this study. The fabric is an open, coarse fabric made of Nomex and fiberglass, designed for use at high temperature.

The data acquisition system collected data at rates of 1000 Hz or higher, giving at least 800 temperature readings for each thermocouple during a 0.8-second data window. A FORTRAN program to obtain heat flux from thermocouple data was modified for the current study. The heat flux calculations are based on the theory of heat transfer in a semi-infinite body at uniform temperature. If the initial temperature of the body is known, then an analytical relation between heat flux at its surface and surface temperature drop can be applied. The key equation is

$$q(t) = \frac{k}{\sqrt{\pi\alpha}} \int_0^t \frac{dT(\tau)}{d\tau} \frac{d\tau}{\sqrt{(t-\tau)}} \tag{1}$$

where q(t) is the heat flux at time t; k is the thermal conductivity of the solid; α is the thermal diffusivity of the solid; and $T(\tau)$ is the measured surface temperature at time τ, where τ is a dummy variable in the integrand (8). The integral must be evaluated at each time t. A simplified numerical procedure is used to solve Equation (1), as described by Nanigian (9). The use of erodable surface thermocouples for heat flux measurement and the numerical scheme for the heat flux computations have been tested and validated in several ways by IPST and Nanmac personnel.

Paper types for this study included 205-gsm recycled linerboard, 205-gsm virgin linerboard, and 130- and 89-gsm fine papers from a Flambeau Papers mill. All four papers were shipped as dried product. Disks 12.7 cm in diameter were cut from the provided sheets and immersed in water for several minutes, then removed and weighed. Moisture levels were typically at 50% or higher after soaking. (All moisture levels reported here are based on average bone-dry weights.) To achieve the desired level of 40% moisture, sheets that were to be preheated were first exposed to room temperature air to bring the moisture level down to around 45%. Tests were done several times for each paper type to determine the level of excess moisture needed before preheating to result in a sheet at 40% moisture after preheating. Sheets that would not be preheated were dried to a moisture level of 40%. The moist sheets were stored in plastic bags at this moisture level for several hours prior to use to ensure uniform moisture distributions.

Sheet preheating proved to be one of the most difficult aspects of this study. Preheating was done by sealing each sample between two metal disks of the same diameter, with Teflon tape stretched around the edges to complete the seal. The sealed sample plus metal disks and tape were weighed and placed in an oven at about 95°C for fixed intervals to preheat the sheet to above 80°C (85°C was targeted). Thermocouples were used several times to ensure that proper preheating did occur during the heating in the oven. When the sealed sample and metal disks were removed from the oven, the hot assembly was quickly weighed. The tape was then stripped off, and the hot, moist sheet was rapidly placed on the dryer fabric, and the activation switch was depressed, causing the pneumatic cylinder to lift the sample up to the drying surface. Unfortunately, two to four seconds could elapse after exposing the sheet to the atmosphere before the drying event began, allowing cooling and moisture loss. After the drying event, the sheet was weighed. The tape and metal disks together were also weighed to permit determination of the initial hot sample weight by difference. Some moisture loss did occur during preheating, requiring sheets typically at about 45% moisture levels to be put into the oven to give sheets at 40% moisture after preheating.

RESULTS AND ANALYSIS

Characteristic Heat Flux Results

Figures 3-5 show typical heat flux curves from a variety of experimental tests. Typical heat flux curves show a peak during the time of pressure rise, followed by a decreasing tail that often decreases roughly according to 1/time^n, with n usually between 0.5 and 1. The tail drops to zero when contact with the paper ceases. These heat flux curves can be largely explained in terms of transient conduction theory (10). Many factors can modify the shape of the heat flux curve. The rise to peak heat flux is related to applied pressure and the ramp rate. The magnitude of heat flux is related to sheet moisture and temperature, factors which are subject to scatter. Mechanical pressure oscillations, which could not be completely removed from the system, may cause some oscillations in heat flux.

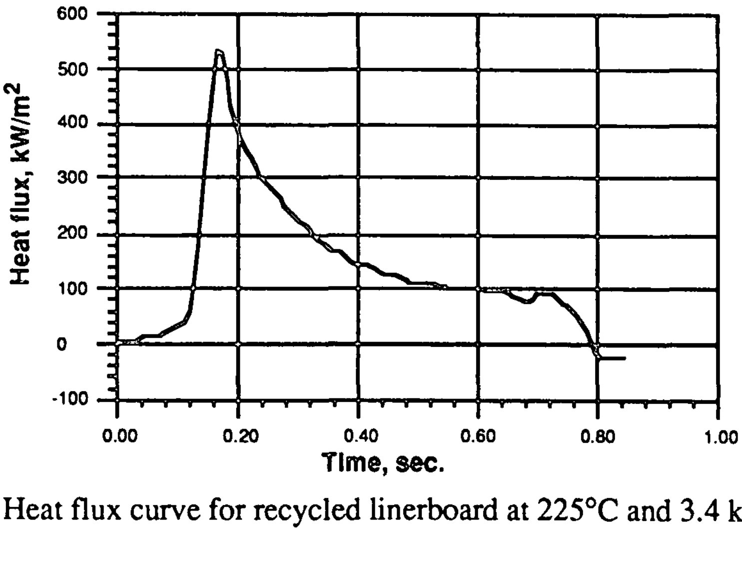

FIGURE 3. Heat flux curve for recycled linerboard at 225°C and 3.4 kPa.

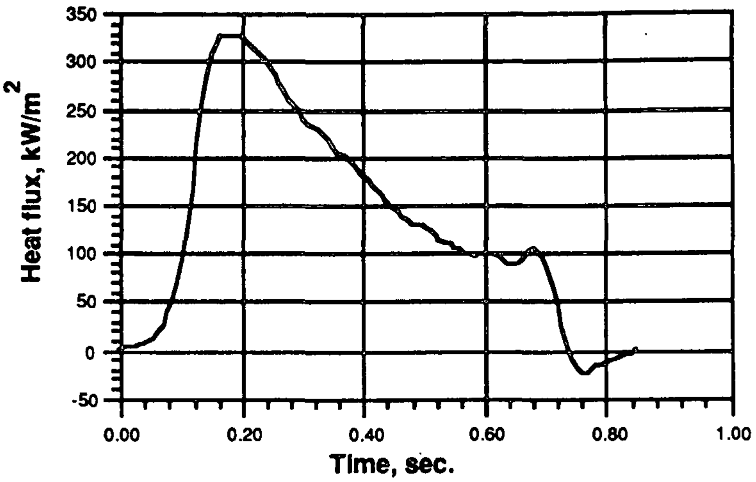

FIGURE 4. Heat flux curve for recycled linerboard at 225°C and 10.3 kPa.

The Effects of Pressure and Temperature in Preheated Sheets

For each series, we will examine the effect of pressure on peak heat flux, time-averaged heat flux, and average drying rate. Peak and average heat flux data are obtained from thermocouple data, while average drying rate is determined from moisture loss and estimated contact time.

Heat flux data can be represented in terms of peak heat flux or average heat flux to the sheet. Both methods lead to essentially the same conclusions, but the average heat flux data were subject to greater errors because of uncertainty in defining the contact time for averaging. This uncertainty arose from differences in ramp rates at different loads. To achieve 0.5 seconds of contact at peak pressure, the electronic timer had to be set for 0.55-0.7 seconds of contact to account for the ramp and descent rates. We will thus focus on peak heat flux results here.

In a typical data set of nine runs (preheated sheets) per test series, up to 27 values of peak heat flux will be available when three thermocouples are used (some sets are discarded if the corresponding heat flux plot indicates obvious errors in the data, such as negative peaks due to a thermocouple that was not at a steady temperature before the run). The average of these peak heat flux values can then be plotted as a single point corresponding to a test series. Figure 5 shows these results for the recycled linerboard test series.

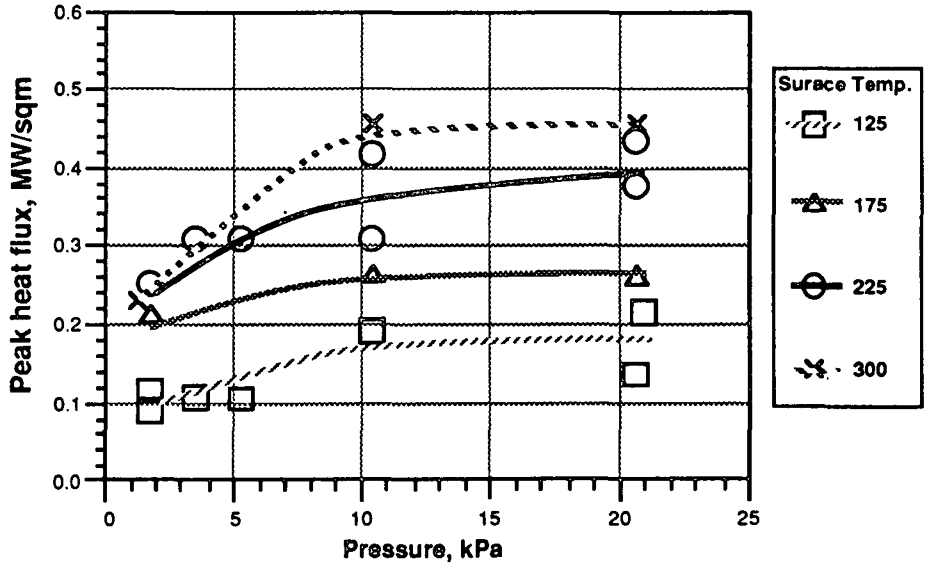

FIGURE 5. Peak heat flux results for the recycled linerboard test series.

In spite of some scatter in the results, an increase in heat flux is apparent as pressure rises to 10 kPa. The gains are small at the two lower temperatures and are much greater above 200°C.

At 225°C (circular symbols), the effect of pressure is now marked. At 10 and 20 kPa, peak heat flux is almost linearly proportional to surface temperature. Near 2 kPa, however, peak heat flux barely changes as temperatures are increased above 175°C. This suggests vapor formation at the high temperature and low mechanical pressure is interfering with heat transfer, inducing a lift off effect that weakens the contact between the paper and the metal. Additional mechanical pressure is required to overcome the force of the vapor and to establish good thermal contact again.

Similar effects can be seen in the data for the other three paper types in Figure 6. The virgin linerboard data at the lowest pressure show no gain in heat transfer as the temperature rises from 225 to 300°C. At higher pressures, peak heat flux becomes more dependent on temperature. The data for the other two papers are insufficient to draw clear conclusions, although at 225°C there appears to be an increase with pressure in the 89-gsm fine paper. Comparison of Figures 6 and 7 shows that the virgin linerboard permits higher peak heat fluxes.

In accounting for the differences in heat flux behavior of sheets at similar temperatures and moisture levels, gas-phase flow data are useful. Paper samples were tested on a Bendtsen porosity device which measures air flow rate at a constant pressure through paper. Paper thickness (required in the calculation of Darcian permeability) was measured with an IPC soft-caliper thickness gauge. The recycled linerboard had a significantly lower permeability than its virgin counterpart, differing by a factor of nearly 7. The difference in permeability may be due to a higher fines content in the recycled board. The lower permeability probably accounts for the lower heat fluxes observed in the recycled paper, for the paper poses more resistance to vapor flow and is more likely to suffer from lift off. However, heat flux can also be affected by many other factors, such as basis weight, sheet density, surface roughness, fiber-water interactions in the sheet, etc.

As with the time-averaged heat flux data, uncertainties in time may taint the time-averaged drying rates. In addition, the drying rate values for preheated sheets are subject to considerable inflation because of the moisture loss that occurs during sheet handling. Drying rate results are nevertheless presented in Figure 7. Possible causes of the high drying rates will be discussed later. Note that several trends already seen in the heat flux data are apparent in the drying rate results. A puzzling observation is the dip in drying rate that seems to occur in going from 1.7 to 3.4 kPa. It seems as if the entire column of data at 1.7 kPa has been shifted upward.

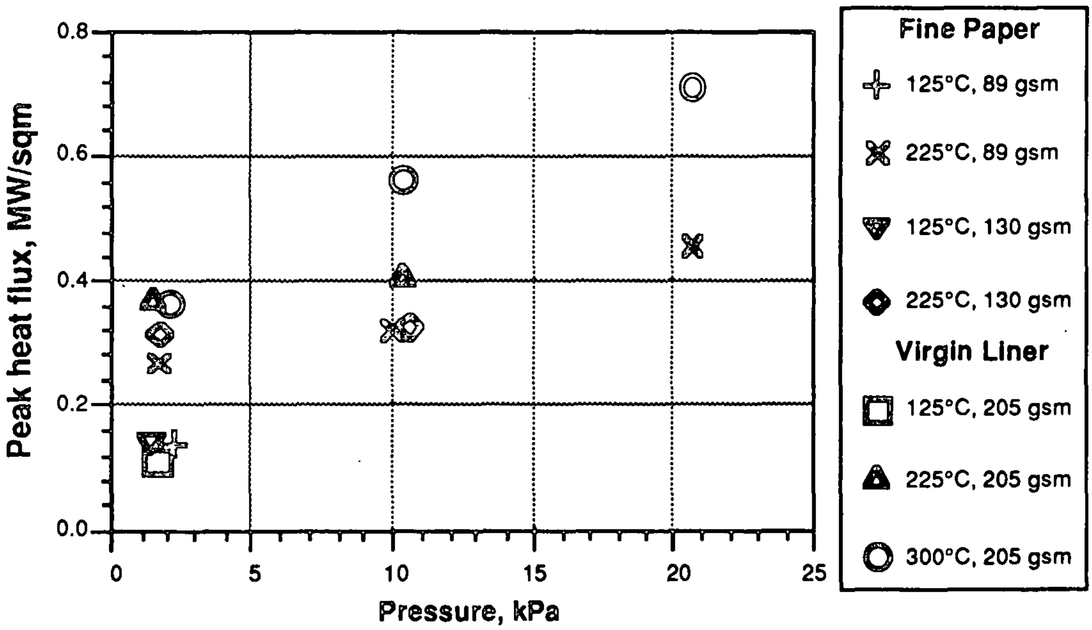

FIGURE 6. Peak heat flux data for fine paper and virgin linerboard samples.

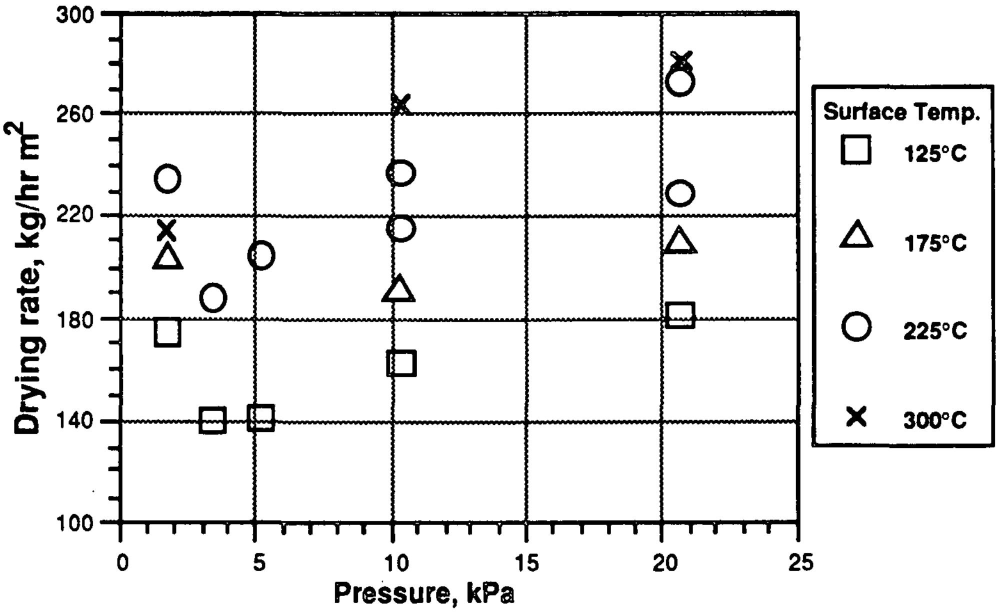

FIGURE 7. Time-averaged drying rates for recycled linerboard samples.

Runs at 1.7 kPa may give higher drying rates than other runs because of the higher ramp rates and the higher overshoot pressures at that condition. As a result, it may be that less time is spent in an inefficient ramp-up zone compared to other runs, or it may be that estimates of contact time at 1.7 kPa have been skewed toward shorter times. In any case, the data at 1.7 kPa do not appear consistent with the data at higher pressures unless one assumes that some systematic source of error has inflated the 1.7-kPa data.

While the trends in Figure 7 may be useful, the absolute values of water removal rates are extremely high. Moisture loss of preheated sheets during sample handling may constitute a substantial (but fairly constant) part of the reported drying rates here. In fact, several tests were done to quantify the moisture loss that occurs during sheet handling. For linerboard, the results indicate that around 100 kg/hr m^2 of the apparent drying rate is due to moisture loss occurring almost immediately as the hot sheet is removed from the hot metal platens and placed on the dryer fabric. Further moisture loss may occur when the sheet is again heated during drying and then removed to be placed on a balance.

Drying rate data for the other paper samples also showed large gains in drying rates with increasing pressure for high-temperature conditions. At 1.7 kPa, drying rates were essentially the same for 225°C and 300°C drying surfaces, probably due to vapor formation effects.

Results with Room-Temperature Sheets

While the focus of this study was on drying of preheated sheets, the uncertainties involved with the preheating method (moisture loss, sheet cooling, and potentially nonuniform moisture distributions) motivated a number of tests with room-temperature sheets. Although the lower sheet temperature limits the applicability of the data, the certainty in initial conditions is an advantage. A number of test series therefore included three runs with room-temperature sheets.

Averaged peak heat fluxes for room-temperature sheets are shown in Figures 8 and 9. Heat flux values are higher than in preheated sheets, where smaller temperature differences exist. At low pressures, heat fluxes are similar for drying at 125°C and 300°C. Sharp increases in peak heat flux with pressure at 300°C were again seen. Similar results were seen in runs with other paper types.

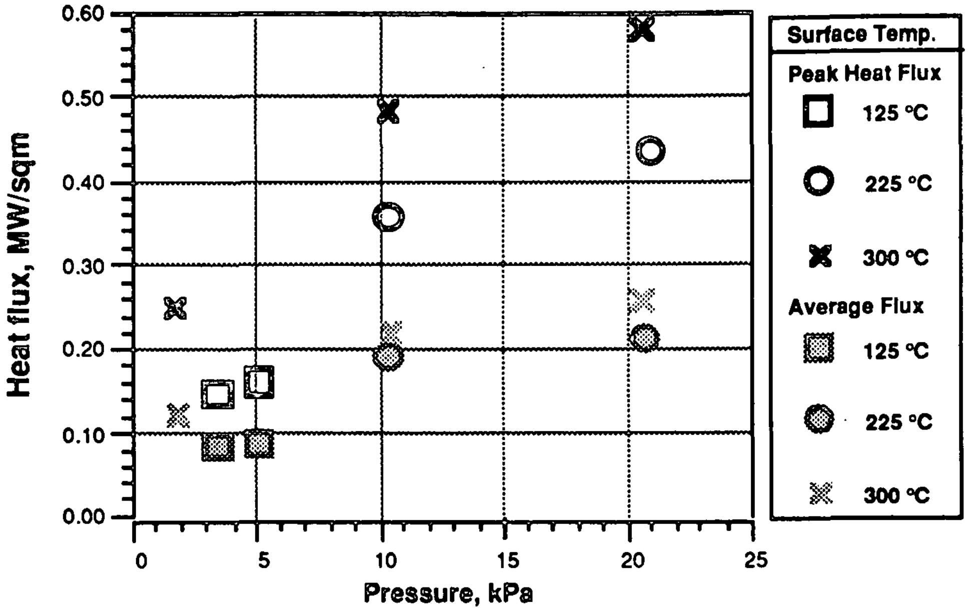

FIGURE 8. Peak and average heat flux in recycled linerboard with room-temperature sheets.

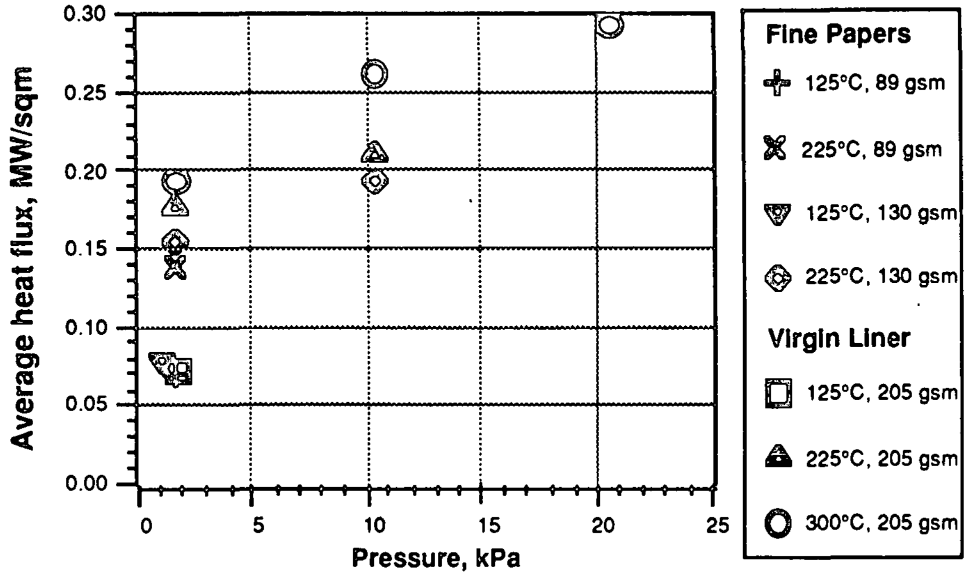

FIGURE 9. Average heat flux data for sheets initially at room temperature.

DISCUSSION

A variety of problems hindered the applicability and reproducibility of the data. The sheet preheating procedure, with its attendant moisture loss and partial sheet cooling, was especially problematic. However, estimates of preheated sheet temperature have been made by comparing heat transfer rates between room-temperature and preheated sheets for low platen temperatures, where lift off phenomena are unlikely to interfere. Based on these estimations, it appears that the preheated sheet may have cooled to 60°C or even lower before the drying event began.

Heat flux data from individual thermocouples in a single run were subject to very large scatter, requiring multiple runs to obtain good average values. Scatter was largely due to the small measurement area of the thermocouples (thin zones about 1 mm long) with respect to the coarser weave of the drying fabric and inherent nonuniformities in paper. Mechanical oscillations in pressure also contributed to the noise. Average values reported for preheated sheets are based upon nine runs with a total of up to 27 transient temperature files, one for each thermocouple. The standard deviation for peak heat flux ranged from 20-100% of the mean value, with about 30% being typical. If 20 samples are used to obtain an estimate of the average peak heat flux, the precision is then approximately ±12% with 95% confidence if the standard deviation is 30% of the mean. Time-averaged heat fluxes were obtained from values of total energy, which is the integral of heat flux over time. The standard deviation of total energy in replicate runs ranged from 10-30%, with 20% being typical. The major source of error, however, was uncertainty in defining the contact time for each applied load; this is a source of error between different levels of applied pressure. Including contact time uncertainty, the overall accuracy of average heat flux results is estimated at ± 35%. Standard deviations for drying rate ranged from 5-25% of the mean values, with 10% being typical. Including the uncertainty in defining contact time, drying rate accuracies are estimated at ±30%.

Compared to industrial drying, the heat flux and moisture loss data reported here are quite high. At 225°C, for example, the maximum average heat flux value was expected to be around 30 kW/m^2, based on total cylinder area, or roughly 60 kW/m^2 based on actual wrap. Our results, however, show typical heat fluxes in linerboard around 150 kW/m^2 at 225°C. Numerous checks of all aspects of the data reduction and analysis procedures ruled out the possibility of mathematical errors. A useful additional check comes by examining observed drying rates corrected for moisture loss due to handling. At 225°C, a representative time-averaged, corrected drying rate is 150 kg/hr m^2. A drying rate of 145 kg/hr m^2 requires 90 kW/m^2 just to vaporize the water. In addition, if the sheet at 60°C must be warmed to 100°C, another 32 kJ/m^2 for a moist 205-gsm sheet is required, which corresponds to an additional heat flux of 64 kW/m^2 in 0.5 seconds. The total heat flux required to sustain an evaporation rate of 145 kg/hr m^2 of water during a 0.5-second event is then 90+64 = 154 kW/m^2. The measured average heat flux value of around 150 kW/m^2 thus appears to be reasonable.

In addition to checks on internal consistency, the heat flux data of this study can be directly compared to some results reported earlier by Ahrens et al. (6,7,11). In (7), for example, Ahrens reports a heat flux curve for moist paper brought in contact with a surface at 220°C with a pressure of 34 kPa. He reported a peak heat flux of about 200 kW/m^2. Using the first 0.5 seconds of his heat flux curve, we obtain an average heat flux near 150 kW/m^2, fully consistent with data reported here. Also in (11), Ahrens and Åström report peak heat flux as a function of mechanical pressure, giving curves for 151°C and 232°C which, upon slight extrapolation, give values about the same as those reported here.

Given that the data may be self-consistent and may agree with related laboratory measurements in the literature, why are the observed values so high? A partially cooled sheet explains part of the higher heat fluxes, but even after correcting for initial temperature, heat transfer is still significantly higher in the laboratory tests than in industrial practice. This can be taken as evidence of inapplicability in the laboratory experiments. On the other hand, instead of asking why the heat fluxes and drying rates in this study are so high, perhaps it would be better to ask why the industrial rates are so low. Further study is needed to properly resolve this important issue.

CONCLUSIONS

A body of data has been established to assist understanding of heat transfer and drying behavior in several paper types, with an emphasis on recycled linerboard. In spite of several limitations in the data, the following conclusions can be drawn:

- Heat transfer can be improved by increasing the pressure on the paper. At low temperatures, the improvement may be slight, but significant gains with pressure are possible at high temperatures (>225°C).

- Lift off reduces heat transfer and drying rates at low pressures and high temperatures.

- Gas-phase permeability may play an important role in drying rates and in controlling the degree of lift off.

- The laboratory drying tests in this study and in related previous studies appear to give heat fluxes well above what is encountered industrially. It is possible that part of the difference is due to factors which are limiting the potential drying rates of drum dryers. Further work is needed to resolve this important issue.

ACKNOWLEDGMENTS

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LITERATURE CITED

1. Haberl, A. 1991. The First Linerboard Application of the Gas Heated Paper Dryer. Proc. CPPA 77th Annual Technical Session, Vol. B., Montreal, Canada.

2. Arenander, S., and Wahren, D. 1983. Impulse Drying Adds New Dimension to Water Removal. Tappi J., 66(9) pp. 123-126.

3. Orloff, D. I. 1992. Impulse Drying of Linerboard: Control of Delamination. J. Pulp Paper Sci., 18(1) pp. J23-J32.

4. Orloff, D. I., and Lindsay, J. D. 1992. The Influence of Yield, Refining and Ingoing Solids on the Impulse Drying Performance of a Ceramic Coated Press Roll. TAPPI 1992 Papermakers Conference, Nashville, Tennessee.

5. Byrd, V. L. 1982. Drying and Heat Transfer Characteristics During Bench-scale Press Drying of Linerboard. Drying '82, ed. A. S. Mujumdar, Hemisphere, Washington, D. C.

6. Ahrens, F.; Kartsounes, G., and Ruff, D. 1984. A Laboratory Study of Hot-surface Drying at High Temperature and Mechanical Loading. Pulp and Paper Canada, 85(3) pp. T63-T67.

7. Ahrens, F. W. 1983. Heat Transfer Aspects of Hot Surface Drying at High Temperature and Mechanical Loading. J. Pulp Paper Sci., 9(3) pp. TR79-TR83.

8. Giedt, W. H. 1955. The Determination of Transient Temperatures and Heat Transfer at a Gas-Metal Interface Applied to a 40-mm Gun Barrel. Jet Propulsion, 25 p. 158.

9. Nanigian, J. 1991. Rocket Igniter Characteristics. NANMAC Temperature Measurement Handbook, Vol. 7, Nanmac Corp., Framingham, MA, 1991, p. L-7.

10. Carslaw, H. S., and Jaeger, J. C. 1947. Conduction of Heat in Solids. Oxford Univ. Press, London , p. 70.

11. Ahrens, F., and Åström, A. 1986. High-Intensity Drying of Paper. Drying Technology, 4(2) pp. 245-270.